Regional Water Stress Analysis with Hydrogen Production at Scale

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Project Start Date: April 2013
Project End Date: Project continuation and direction determined annually by DOE

Overall Objectives

- Incorporate water consumption associated with hydrogen production as a transportation fuel for use in fuel cell electric vehicles (FCEVs).
- Compare water consumption of hydrogen for use in FCEVs with other fuel or vehicle systems on a life cycle basis.
- Identify major contributors in upstream supply chain to water consumption.
- Analyze the technology environmental impacts on regional water stress for hydrogen and fuel cell deployment scenarios.

Fiscal Year (FY) 2018 Objectives

- Quantify and compare water consumption and water stress impacts of electricity generation in different regions of the United States.
- Evaluate the impacts hydrogen FCEV deployment will have on regional water stress in the United States.
- Improve the Available water remaining for the United States (AWARE-US) water stress index.

Technical Barriers

This project directly addresses Technical Barriers B, C, and D in the System Analysis section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.[1] These barriers are as follows.

(B) Stove-Piped/Siloed Analytical Capability

(C) Inconsistent Data, Assumptions, and Guidelines

(D) Insufficient Suite of Models and Tools.

Contribution to Achievement of DOE Systems Analysis Milestones

This project contributes to achievement of the following DOE milestones from the Systems Analysis section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

- Milestone 1.13: Complete environmental analysis of the technology environmental impacts for hydrogen and fuel cell scenarios and technology readiness.
- Milestone 2.2: Annual model update and validation. (4Q, 2011 through 4Q, 2020)

FY 2018 Accomplishments

- Improved the AWARE-US water stress index with new ground water recharge data.
- Estimated water consumption and water use impact of electricity generation in different regions of the United States.
- Performed water consumption impact analysis for the large-scale deployment scenarios of hydrogen FCEVs.

[1] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

INTRODUCTION

Hydrogen is a zero-carbon energy carrier that can be produced from a variety of domestic feedstock sources. Hydrogen is also important for FCEVs and the processing and upgrading of other fuels. Production of energy and transportation fuels, including hydrogen, typically requires the use of freshwater resources. However, freshwater resources available to human use vary substantially across the United States. Large-scale deployment of energy systems in water-stressed regions has the potential to exacerbate water-resource competition among various uses, such as ecosystem services and food and energy production. This means water consumption of energy systems may cause negative environmental and social impacts in water-stressed regions. Thus, water stress analysis at a regional level is critical for a sustainable future of new energy systems.

The objective of this study is to evaluate the impacts of deploying new energy systems (e.g., hydrogen) on the regional water resources in the United States by considering local water supply and demand. Because electricity is a key resource for generating or compressing hydrogen, we evaluated water consumption and water stress impacts associated with electricity generation in the United States using facility-level water consumption data and the newly developed county-level water stress index (AWARE-US). We then analyzed the regional impact of hydrogen production at scale scenarios for FCEVs on water stress. This study contributes information that can be used to guide sustainable water management decisions.

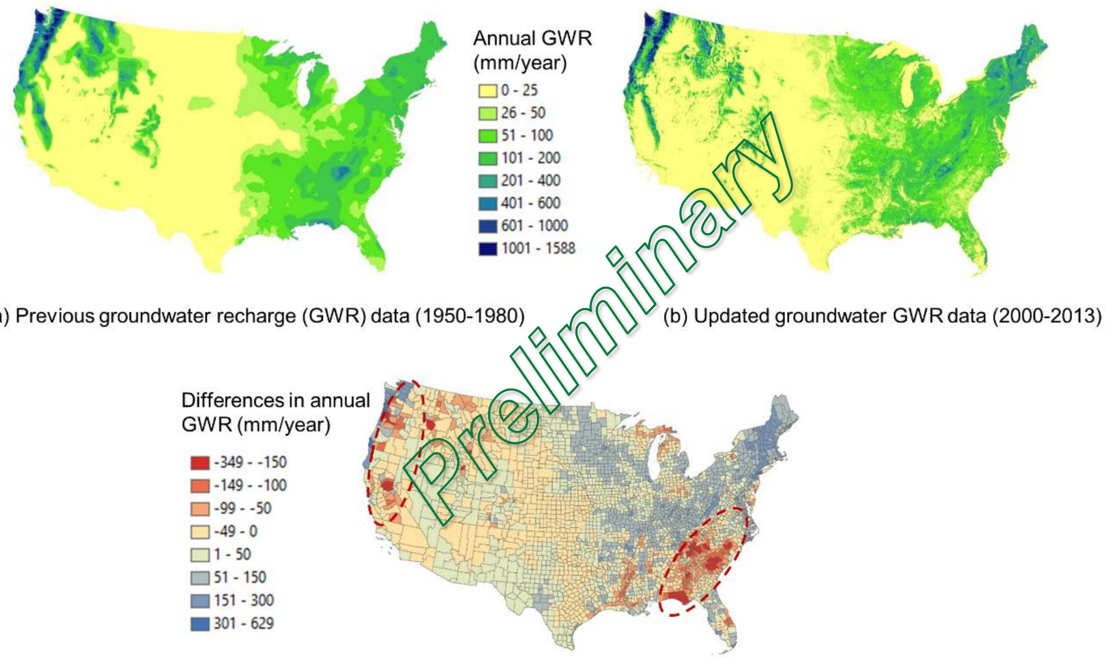
APPROACH

The project includes three major parts: (1) updating the county-level water stress index (AWARE-US), (2) evaluating water stress impacts of hydro and thermoelectricity generation at the regional level, and (3) evaluating regional water stress impacts of hydrogen production associated with 2040 FCEV deployment scenarios. To improve reliability of AWARE-US, we incorporated the latest high-resolution (800 m) groundwater recharge data from the United States Geological Survey (USGS).

To evaluate water use impact of electricity generation, we consider spatial variations in both water consumption and regional water supply because impact of the same amount of water consumption on water stress varies widely across the United States [1]. In this analysis, water use impact is quantified as water scarcity footprint [2]. Water scarcity footprint is calculated as the product of facility-level water consumption factors [3] and county-level characterization factors (CFs) from the updated AWARE-US index [1]. The resulting water scarcity footprint is expressed in terms of U.S. equivalent gallons of water consumption [1]. One U.S. equivalent gallon indicates the impact of one gallon of water consumption in a region that has the U.S. average amount of water availability. Because water consumption in different regions can be expressed as equivalent gallons of water consumption, AWARE-US enables systematic comparison of the water consumption impacts across regions. Finally, Argonne evaluated the regional water use impact associated with hydrogen demand for FCEVs by combining estimated water consumption for hydrogen production and the AWARE-US index. Consistent with the H2@Scale initiative, we assume electricity is used for hydrogen production when wind/solar/nuclear is used for electricity generation. When renewable resources are not available, steam methane reforming (SMR) of natural gas is used for hydrogen production.

RESULTS

Figure 1 shows improvements in the groundwater recharge (GWR) data used in AWARE-US. Previously, we used the 1950–1980 annual GWR data (Figure 1a) from USGS, which was the only national data available at the time when we initially developed AWARE-US. To reflect more recent data, we incorporated the latest national-level, high-resolution (800 m) GWR data from USGS [4] (Figure 1b). We found overall patterns are similar between the old and updated GWR datasets, but large differences are observed when examined at the county level. Specifically, differences in annual GWR can be as high as 300 mm/year (Figure 1c). Comparing to the old dataset, the updated GWR rate is much lower (difference >100 mm/year) for many counties in southeastern states, northern California, and western Oregon, but much higher (difference >150 mm/year) in the Corn Belt and New England regions (Figure 1c). In AWARE-US, GWR is part of the natural runoff (renewable freshwater resources). In certain areas, usage of groundwater may exceed GWR, which means non-renewable water resources will be used. This may cause problems like groundwater depletion and ecosystem degradation. Improved GWR data allows us to better differentiate human water consumption sourced from renewable versus non-renewable groundwater. It also improves reliability of AWARE-US, especially in regions relying on groundwater resources.

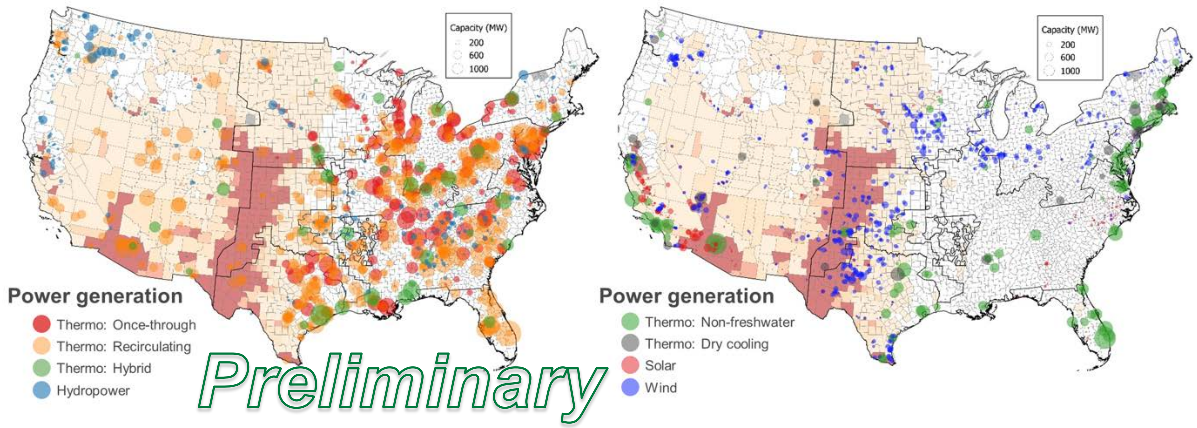


(a) Previous groundwater recharge (GWR) data (1950-1980) (b) Updated groundwater GWR data (2000-2013)

(c) Differences in annual GWR rates at the county level

Figure 1. Updated groundwater recharge data for AWARE-US

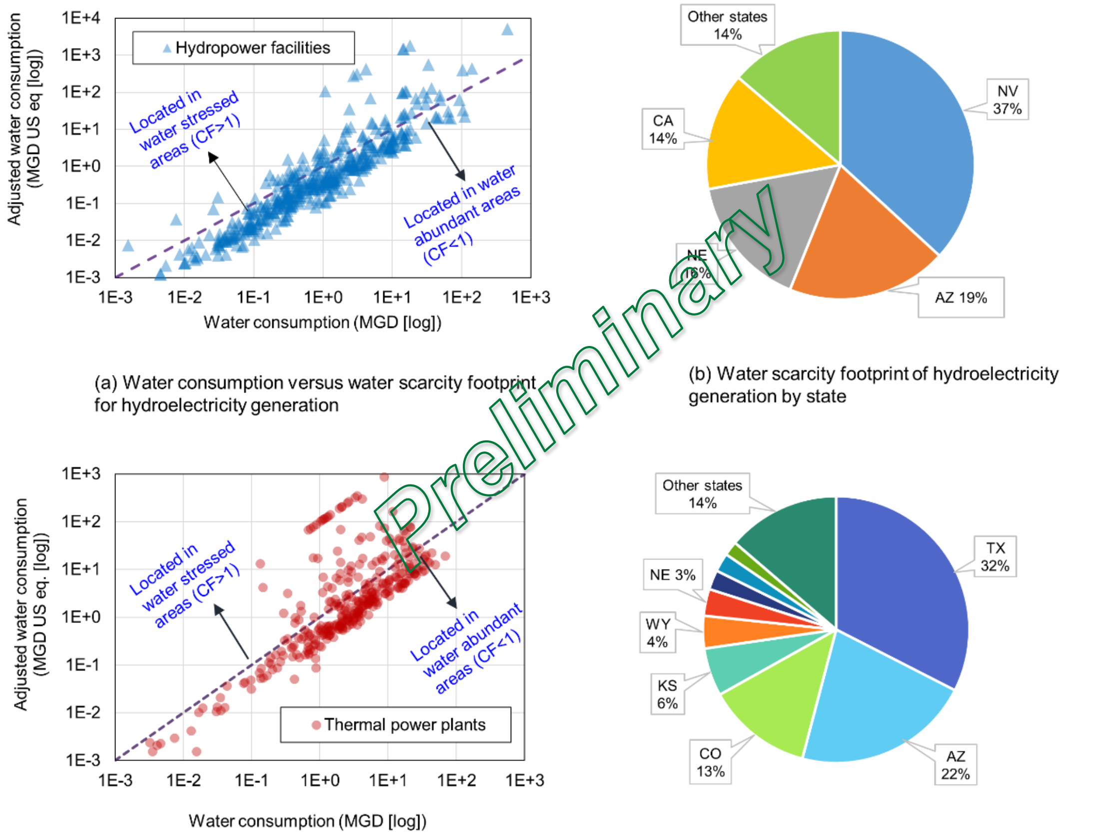
Figure 2 illustrates the regional trend of electricity generation, which indicates that the power sector has adapted to varying energy resources and freshwater availability. We found regions in water-stressed areas tend to use technologies not involving freshwater consumption for electricity generation (Figure 2a). For instance, wind-power plants are concentrated in the High Plains and Texas where water stress is much higher than neighboring regions. There are some wind-power clusters in Midwestern states like Iowa, but these clusters are driven more by wind resources and policies rather than by shortages of water resources. In the southwestern United States, solar, wind, and non-freshwater (e.g., reclaimed water) resources have been utilized to address water shortage issues in this region. Although non-freshwater power generation has already been deployed in various semi-arid regions, electricity generation from these facilities is still small compared to traditional thermal and hydropower generations. For power plants relying on freshwater, those with the highest capacities (≥1,000 MWh) are mostly located in the eastern United States (Figure 2b). Because freshwater water is relatively abundant in this area, once-through technology is still widely used for thermoelectricity generation, but circulating technology is also a popular option. In the Western United States, thermal power generation mostly uses recirculating rather than once-through technology.



(a) Distribution of power generation uses freshwater (b) Distribution of non-freshwater power generation

Figure 2. Spatial distribution of power generation by energy source and technology

When regional water stress is considered, we found that a majority of existing thermal and hydropower plants that use freshwater are located in water-abundant regions (AWARE-US CF<1) (Figure 3). However, about 23% of thermal power plants and 18% of hydropower plants (by power generation) are located in water-stressed regions (AWARE-US CF>1). For the 23% thermal power plants, about 91% have already adopted recirculation-cooling technology to reduce cooling water withdrawal. Due to varying water stress, spatial distribution patterns of water consumption versus water use impact are very different, especially in the western United States, where water use impact can be 100 times higher than indicated by water consumption. While water consumption of thermal power generation is higher in the eastern United States, water use impact (water scarcity footprint) is higher in the southwestern United States, primarily due to limited freshwater supply. At the state level, Texas, Arizona, Colorado, and Kansas contributed the most to the overall water scarcity footprint (73%) (Figure 3b), but they only contribute 17% of total thermal power generation. For hydropower, we found constrained water resources make the water scarcity footprint of hydropower amplify water constraints in water-stressed regions (e.g., Colorado River, San Joaquin River). Spatially, due to high evaporation rate, water consumption for hydropower (evaporation from reservoirs) is higher in the southern United States. At the state level, 86% of the total hydropower water scarcity footprint comes from Nevada, Arizona, Nebraska, and California. Reducing hydropower water consumption can be difficult because evaporation rates are primarily determined by local climate. In addition, large reservoirs used for hydropower generation are often built for multiple purposes (e.g., navigation, irrigation, flood control). Thus, reducing the water impact of multipurpose dams requires coordinated efforts of all stakeholders.



(a) Water consumption versus water scarcity footprint for hydroelectricity generation

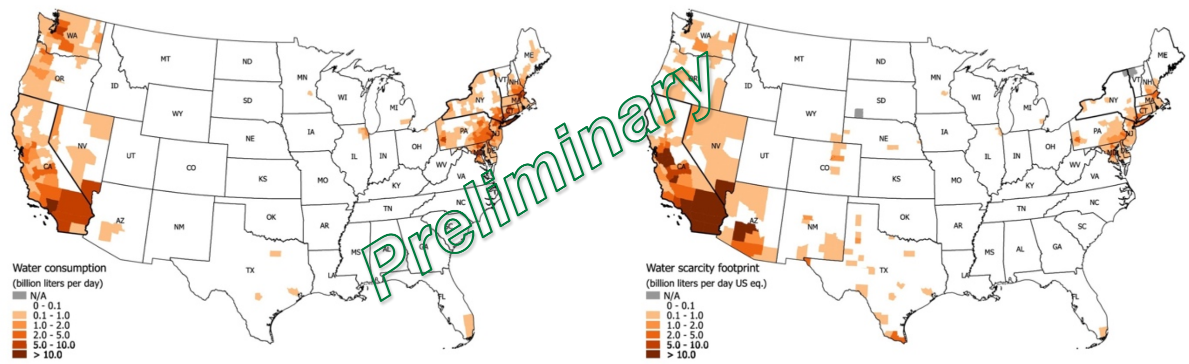
(b) Water scarcity footprint of hydroelectricity generation by state

(c) Water consumption versus water scarcity footprint for thermoelectricity generation

(d) Water scarcity footprint of thermoelectricity generation by state

Figure 3. Water consumption and water scarcity footprint for hydroelectricity (a,b) and thermoelectricity generation (c,d)

Figure 4 shows water consumption and water use impact of FCEV deployment scenarios at the county level. Water demand of hydrogen production includes local water consumption and upstream water input (e.g., water embedded in electricity). Comparison of water consumption (Figure 4a) and water use impact (Figure 4b) suggests that implications of water consumption on regional water stress for hydrogen FCEV deployment differ by region. We found that water consumptions of hydrogen production are highest in the Pacific coastal and the northeastern coastal areas (Figure 4a), primarily due to the projected distribution of FCEVs [1]. Water consumption alone, however, does not reflect differences in regional water stress. Figure 4b represents water use impact of FCEVs at the county level and considers both consumption and water stress, expressed in water scarcity footprint. The results suggest that the western United States would have much higher water use impact compared to the eastern United States. For example, using one FCEV deployment scenario, California consumes only 1.3 times the volume of freshwater consumed in New York in order to meet the hydrogen demand in their respective states. However, the water consumption impact in California is 27 times higher compared to New York due to higher water stress status in California.



a) Water consumption for H_2 FCEVs b) Water scarcity footprint for H_2 FCEVs

Figure 4. County-level water consumption versus water scarcity footprint for hydrogen production used for FCEVs in 2040

CONCLUSIONS AND UPCOMING ACTIVITIES

This analysis focused on identifying water use impact of electricity generation and large-scale deployment of hydrogen FCEVs. The results illustrate that regional variation exists for water use impact of electricity generation and FCEV deployment. The spatial trend of electricity generation suggests that the power sector has already adapted to varying water availability by using non-freshwater resources (wind/solar/nuclear/reclaimed water) in water-stressed regions. We found a majority of power plants (80%) are located in water-abundant regions. At the state level, Texas, Arizona, Colorado, and Kansas contributed 73% of water scarcity footprint of thermal power generation in water-stressed regions. For hydropower electricity, Nevada, Arizona, Nebraska, and California contributed 88% of the water scarcity in water-stressed regions. For future energy systems deployment, such as FCEVs, any marginal increase in water demand in water-stressed regions will magnify the impact on water stress. This study provides a systematic approach to evaluate the sustainability of various energy systems in terms of water use and its impact on water stress in various regions in the United States.

For upcoming activities, we will focus on three major areas: (1) updating AWARE-US with the latest water consumption data, (2) developing a monthly/seasonal AWARE-US database, and (3) developing regional supply-demand databases. Accurate and timely human water consumption estimates are critical for evaluating water stress conditions. Currently AWARE-US uses 2010 withdrawal data along with consumption factors derived from the 1995 water use report. In FY19, we will upgrade AWARE-US with water consumption data from the 2015 water use report. Furthermore, current AWARE-US evaluates water use impact on an annual basis, but both water demand and water supply can vary substantially from month to month. To address this issue, subsequent studies will develop a monthly version of AWARE-US to enable seasonal water impact analysis in FY19. Finally, we will start to build a regional database that shows supply and demand of major fuels (hydrogen, electricity, gasoline, diesel, and biofuel) at a regional level. We will estimate water consumption and water use impact associated with the production of each fuel and incorporate them into the regional database.

FY 2018 PUBLICATIONS/PRESENTATIONS

1. Uisung Lee, Hui Xu, Jesse Daystar, Amgad Elgowainy, and Michael Wang “AWARE-US: Quantifying Water Stress Impacts of Energy Systems in the United States.” *Science of The Total Environment* 648 (January 2019): 1313–22.
2. Amgad Elgowainy, Uisung Lee, Hui Xu, and Michael Wang. “Regional water stress analysis with hydrogen production at scale.” Poster presentation, DOE Hydrogen and Fuel Cells Program Annual Merit Review, Washington DC, June 14, 2018.

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1. Uisung Lee, Hui Xu, Jesse Daystar, Amgad Elgowainy, and Michael Wang. "AWARE-US: Quantifying Water Stress Impacts of Energy Systems in the United States." *Science of The Total Environment* 648 (January 2019): 1313–22. https://doi.org/10.1016/j.scitotenv.2018.08.250.
2. ISO. "14046 Water Footprint—Principles, Requirements and Guidelines," (2014).
3. Uisung Lee, Jeongwoo Han, Amgad Elgowainy, and Michael Wang. "Regional Water Consumption for Hydro and Thermal Electricity Generation in the United States." *Applied Energy* 210 (January 2018): 661–72. https://doi.org/10.1016/j.apenergy.2017.05.025.
4. M. Reitz, W.E. Sanford, G.B. Senay, and J. Cazenas. "Annual Estimates of Recharge, Quick-Flow Runoff, and Evapotranspiration for the Contiguous U.S. Using Empirical Regression Equations." *JAWRA Journal of the American Water Resources Association* 53 (August 2017): 961–83. https://doi.org/10.1111/1752-1688.12546.